

Puzzles in charmonium decays

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Abstract

The open charm effects via intermediate hadron loop transitions seem to play a crucial role in the understanding of several existing “puzzles” in charmonium exclusive decays, such as the $\psi(3770)$ non- $D\bar{D}$ decays, and “ $\rho\pi$ puzzle” etc. In the charmonium energy region, non-perturbative mechanisms could be still sizeable, and as a consequence the intermediate hadron loop transitions also provide a mechanism for the helicity-selection-rule (HSR) violation. We report our recent progress on those existing puzzles.

Keywords:

Charmonium decays, Helicity selection rule violation, Intermediate meson loop transitions

1. Helicity selection rule violations and open charm effects in charmonium decays

The exclusive decays of heavy quarkonium have been an important platform for studying the nature of strong interactions in the literature [1–6] since the discovery of quantum chromodynamics (QCD). An interesting issue in charmonium decays is the effects arising from open charmed meson channels. For charmonia which are close to an open charmed meson channel, and if they have also strong couplings to the open channel, one would expect that such an open channel can affect properties of the charmonia in both spectra and decays. An immediate example is the $D\bar{D}$ threshold ($m_{D\bar{D}} \simeq 3.72$ GeV), below and above which the $\psi(3686)$ and $\psi(3770)$ sit closely. An interesting and nontrivial question here is whether the $\psi(3770)$ decay is totally saturated by $D\bar{D}$, or whether there exist significant non- $D\bar{D}$ decay channels [7–13].

Unfortunately, a definite answer from either experiment or theory is unavailable. In experiment, the $D\bar{D}$ cross section measurement by CLEO Collaboration suggests that the maximum non- $D\bar{D}$ branching ratio is about 6.8% [14–16], while BES Collaboration find much larger non- $D\bar{D}$ branching ratios of $\sim 15\%$ in the direct measurement of non- $D\bar{D}$ inclusive cross section [17]. In theory, next-to-leading-order (NLO) pQCD

calculation of the $c\bar{c}$ annihilation width for $\psi(3770)$ leads to a maximum of about 5% for the $\psi(3770)$ non- $D\bar{D}$ decay branching ratio [18], which appears to favor a relatively smaller non- $D\bar{D}$ branching ratio. However, as shown in Ref. [18], the NLO corrections are the same order as the leading order results. It would jeopardize the validity of the perturbation expansion on the one hand, and on the other hand, raises the question about the contributions from non-pQCD mechanisms.

A relevant issue in exclusive processes is the so-called helicity selection rule (HSR) [1, 2] which provides a guidance for expectations of perturbative QCD (pQCD) asymptotic behaviors [1–6] that can be examined in experiment. However, in comparison with the accumulated data, more and more observations suggest significant discrepancies between the data and the selection-rule expectations. As an example, the decays of $J/\psi \rightarrow VP$ and $\eta_c \rightarrow VV$ would be suppressed by this rule [19]. In reality, they are rather important decay channels for J/ψ and η_c , respectively [20]. One possible reason why the perturbative method fails here could be that although the mass of the charm quark is heavy, it is, however, not as heavy as pQCD demands. Therefore, it is not safe to apply the helicity selection rule to charmonium decays (One may anticipate that the situation should be improved in bottomonium decays).

In this proceeding, we report our study of the intermediate meson loop effects in several HSR-violating channels, which serves as a solution for our understanding of several puzzling problems, i.e. $\psi(3770)$ non- $D\bar{D}$ decay,

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“ $\rho\pi$ puzzle”, and χ_{cJ} ’s HSR-violating decays.

2. Non- $D\bar{D}$ decay of $\psi(3770)$

The puzzling situation with the $\psi(3770)$ non- $D\bar{D}$ decay branching ratio could be a handle for putting pieces of information together in charmonium exclusive decays. The dominant decay of $\psi(3770) \rightarrow D\bar{D}$ implies possible significant branching ratios for $\psi(3770) \rightarrow \text{non-}D\bar{D}$ via a long-range interaction mechanism. We argue that the intermediate $D\bar{D}$ and $D\bar{D}^* + c.c.$ rescatterings, which annihilate the $c\bar{c}$ at relatively large distance by the OZI-rule evading processes, may provide a natural mechanism for quantifying the $\psi(3770)$ non- $D\bar{D}$ decays [21]. Since $\psi(3770)$ is above the $D\bar{D}$ threshold, this contribution has an absorptive part, for which the quantitative results can be pursued.

We investigate the exclusive decay of $\psi(3770) \rightarrow VP$, where V and P stand for light vector and pseudoscalar meson, respectively. This type of transitions is supposed to be suppressed by the HSR at QCD leading twist similar to $J/\psi \rightarrow VP$. However, the non-pQCD transitions via intermediate meson loop contributions could be a mechanism evading not only the OZI rule but also the HSR.

An apparent advantage in $\psi(3770) \rightarrow VP$ is that we can benefit from the unique Lorentz structure of anti-symmetric tensor coupling. In principle, all possible transition mechanisms will contribute to the corrections to the VVP coupling form factor. Thus, we can make the following parametrization for $\psi(3770) \rightarrow VP$:

$$\mathcal{M}_{fi} \equiv i(g_L + e^{i\delta} g_S \mathcal{F}_S(\vec{p}_V)) \times \varepsilon_{\alpha\beta\mu\nu} P_\psi^\alpha \epsilon_\psi^\beta P_V^\mu \epsilon_V^{*\nu} / M_{\psi(3770)} \quad (1)$$

where g_L denotes the intermediate meson loop amplitude, and g_S describes the production of two pairs of $q\bar{q}$ in the final VP via OZI singly disconnected (SOZI) transitions. The coupling g_S is related to the short-range contributions. Hence, we assume that the SU(3) flavor symmetry will connect all the light VP production channels via

$$g_S^{\rho^0\pi^0} : g_S^{K^{*+}K^-} : g_S^{\omega\eta} : g_S^{\omega\eta'} : g_S^{\phi\eta} : g_S^{\phi\eta'} = 1 : 1 : \cos\alpha_P : \sin\alpha_P : (-\sin\alpha_P) : \cos\alpha_P, \quad (2)$$

with the other isospin channels implicated. The angle $\alpha_P \equiv \theta_P + \arctan(\sqrt{2})$ is η and η' mixing angle. A conventional form factor, $\mathcal{F}_S^2(\vec{p}_V) \equiv \exp(-\vec{p}_V^2/8\beta^2)$ with $\beta = 0.5\text{GeV}$, is applied for the SOZI transition with \vec{p}_V the final three momentum in the $\psi(3770)$ rest frame [22, 23]. The introduction of hadronic degrees

of freedom via the meson loops may lead to a relative phase δ between g_L and g_S terms.

In Fig. 1, the intermediate meson loops recognized as t - and s -channel transitions are illustrated. The following effective Lagrangians are adopted to evaluate the transition amplitudes related to g_L ,

$$\begin{aligned} \mathcal{L}_{\psi D\bar{D}} &= g_{\psi D\bar{D}} \{D\partial_\mu \bar{D} - \partial_\mu D\bar{D}\} \psi^\mu, \\ \mathcal{L}_{\psi D\bar{D}^*} &= -ig_{\psi D\bar{D}^*} \epsilon_{\alpha\beta\mu\nu} \partial^\alpha \psi^\beta \partial^\mu \bar{D}^{*\nu} D + H.c., \\ \mathcal{L}_{\mathcal{P} D^* \bar{D}^*} &= -ig_{\mathcal{P} D^* \bar{D}^*} \epsilon_{\alpha\beta\mu\nu} \partial^\alpha D^{*\beta} \partial^\mu \bar{D}^{*\nu} \mathcal{P} + H.c., \\ \mathcal{L}_{\mathcal{P} \bar{D} D^*} &= g_{D^* \mathcal{P} \bar{D}} \{\bar{D}\partial_\mu \mathcal{P} - \partial_\mu \bar{D}\mathcal{P}\} D^{*\mu} + H.c., \end{aligned} \quad (3)$$

where $\epsilon_{\alpha\beta\mu\nu}$ is the Levi-Civita tensor; \mathcal{P} and \mathcal{V}^β are the pseudoscalar and vector meson fields, respectively.

The charmed meson couplings to light meson are obtained in the chiral and heavy quark limits [24],

$$\begin{aligned} g_{D^* D \pi} &= \frac{2}{f_\pi} g \sqrt{m_D m_{D^*}}, & g_{D^* D^* \pi} &= \frac{g_{D^* D \pi}}{\tilde{M}_D}, \\ g_{D^* D \rho} &= \sqrt{2} \lambda g_\rho, & g_{DD\rho} &= g_{D^* D \rho} \tilde{M}_D, \end{aligned} \quad (4)$$

where $f_\pi = 132$ MeV is the pion decay constant, and $\tilde{M}_D \equiv \sqrt{m_D m_{D^*}}$ sets a mass scale. The parameters g_ρ respects the relation $g_\rho = m_\rho/f_\pi$ [25]. We take $\lambda = 0.56 \text{ GeV}^{-1}$ and $\alpha = 0.59$ [26, 27]

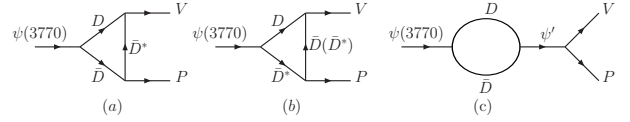


Figure 1: The t [(a) and (b)] and s -channel (c) meson loops in $\psi(3770) \rightarrow VP$.

Note that the t -channel loops suffer from divergence [28]. A dipole form factor is thus introduced to kill the divergence and also compensate the off-shell effects arising from virtual particle exchanges:

$$\mathcal{F}(q^2) = \left(\frac{\Lambda^2 - m_{ex}^2}{\Lambda^2 - q^2} \right)^2, \quad (5)$$

where $\Lambda \equiv m_{ex} + \alpha \Lambda_{QCD}$, with $\Lambda_{QCD} = 0.22 \text{ GeV}$; m_{ex} is the mass of the exchanged meson and α is a parameter to be determined by experimental data for $\psi(3770) \rightarrow J/\psi\eta$. The detailed formulae, which we skip here, can be found in Ref. [21].

We use the measured $\psi(3770) \rightarrow J/\psi\eta$ to constrain the form factor parameter α . Note that the momentum carried by the final state mesons is rather small. This is an indication that the gluon exchanges are very soft. We hence assume that the short-distance pQCD processes are strongly suppressed, and the transition is dominated

by the long-distance transition mechanism via intermediate meson loops. With $BR_{J/\psi\eta}^{exp} = (9.0 \pm 4) \times 10^{-4}$ [20], $\alpha = 1.73$ can be determined and the exclusive t -channel contributes 8.44×10^{-4} to the branching ratio.

By applying the experimental data, $BR_{\phi\eta} = (3.1 \pm 0.7) \times 10^{-4}$ [20] and $BR_{\rho\pi} < 0.24\%$ with C.L. of 90% [29], we can constrain the coupling g_S and phase angle δ . Other channels can then be predicted [21].

Table 1: Branching ratios for $\psi(3770) \rightarrow VP$ calculated for different mechanisms. The values for $J/\psi\eta$ and $\phi\eta$ are fixed at the central values of the experimental data [20], and the experimental upper limit is taken for $\rho\pi$ [29].

BR($\times 10^{-4}$)	Total	Exp.
$J/\psi\eta$	9.0	9.0 ± 4.0
$J/\psi\pi^0$	4.4×10^{-2}	< 2.8
$\rho\pi$	24.0	< 24.0 [29]
$K^{*+}K^- + c.c$	8.91	not seen
$K^{*0}\bar{K}^0 + c.c$	9.90	not seen
$\phi\eta$	3.1	3.1 ± 0.7
$\phi\eta'$	3.78	not seen
$\omega\eta$	4.69	not seen
$\omega\eta'$	0.39	not seen
$\rho\eta$	1.8×10^{-2}	not seen
$\rho\eta'$	1.0×10^{-2}	not seen
$\omega\pi^0$	2.5×10^{-2}	not seen
Sum	63.87	-

In Tab. 1, the results for all VP channels are listed. The exclusive branching ratios given by the t - and s -channels, and SOZI transitions can be found in Ref. [21]. Remember that the input channels are $\psi(3770) \rightarrow J/\psi\eta$, $\phi\eta$ and $\rho\pi$, where the experimental upper limit for $\rho\pi$ suggests a correlation between the SOZI transition coupling g_S and the phase angle δ . By varying δ , but keeping the $\phi\eta$ rate unchanged (i.e. g_S will be changed), we obtain a bound for the sum of branching ratios, $\simeq (0.41 - 0.64)\%$. We refer readers to Ref. [21] for the detailed calculation, and only summarize the conclusive points as follows:

i) It is interesting to see that the intermediate D meson loop transitions indeed account for some deficit for the non- $D\bar{D}$ decay. In particular, the t -channel transitions illustrated in Fig. 1 contribute dominantly to the decay amplitudes. In contrast, in most cases, the SOZI and s -channel transitions are found rather small [21].

ii) The sum of those VP channel contributions accounts for the branching ratio of $(0.41 - 0.64)\%$ in the $\psi(3770)$ non- $D\bar{D}$ decays. This appears to be a small fraction. However, notice that $\psi(3770)$ opens to a large number of light meson decay channels. A sum

of all those channels may result in a sizeable non- $D\bar{D}$ branching ratio. High statistic experiment at BEPCII [6] should be able to measure more exclusive decay channels of $\psi(3770)$, which will be able to provide a direct test of our mode calculations.

iii) We stress again that our calculation of $\psi(3770) \rightarrow VP$ benefits from the unique property of the VVP coupling. It allows a reliable constraint on the model parameters. For other exclusive channels, e.g. $\psi(3770) \rightarrow VS$ and VT , the vertex couplings become complicated. Numerical calculations of the intermediate meson loops would become strongly model-dependent. Qualitatively, the results for $\psi(3770) \rightarrow VP$ provide an idea that how large an exclusive decay branching ratio would be in the $\psi(3770)$ non- $D\bar{D}$ decays [30].

3. Brief comments on the “ $\rho\pi$ puzzle”

As mentioned earlier, the decay of $\psi(3770) \rightarrow VP$ also violates the HSR at pQCD leading twist. Therefore, the intermediate meson loop transitions provide a non-perturbative mechanism for evading the HSR. A natural conjecture is that such a mechanism may also play a role in $\psi' \rightarrow VP$. Since the mass of $\psi(3686)$ is located in the vicinity of the open $D\bar{D}$ threshold, it would experience much more significant effects from the open channels than $J/\psi \rightarrow VP$. In this sense, the non-perturbative intermediate meson loop transitions could be correlated with the “ $\rho\pi$ puzzle” in the literature.

As shown in Refs. [23, 31], there exists an overall suppression on the short-range strong decay strength of $\psi(3686) \rightarrow VP$, not just in $\psi(3686) \rightarrow \rho\pi$. Due to this suppression, the EM transition amplitudes become compatible with the strong decay amplitudes with which the interferences produce deviations from the naive expectations based on the SOZI transition mechanism. To be more specific, due to the interference, the $\rho\pi$ decay is further suppressed, i.e. causes the so-called “ $\rho\pi$ puzzle”. Also, the neutral $K^{*0}\bar{K}^0 + c.c$ has a much larger branching ratio than the charged one $K^{*+}K^- + c.c$. [20].

For $J/\psi \rightarrow VP$, since the mass of J/ψ is far below the $D\bar{D}$ threshold, the open charm effects via the intermediate meson loops are negligibly small. The overall branching ratios for $J/\psi \rightarrow VP$ can be well described by the SOZI and EM transitions with a proper phase [23, 31].

We emphasize that the EM transitions also play an important role. This can be easily recognized by the observation that the isospin-violating decay channels, J/ψ and $\psi(3686) \rightarrow \rho\eta$ and $\rho\eta'$ have branching ratios compatible with those isospin conserved ones such as $\omega\eta$, $\omega\eta'$, $\phi\eta$ and $\phi\eta'$ [20]. These channels are found respect

“12% rule” pretty well and can be well understood in vector meson dominance (VMD) model [23, 31].

4. Further evidences for intermediate meson loops

As a natural mechanism for evading the OZI rule and HSR, and a rather general non-perturbative scenario in the charmonium energy region, the intermediate meson loops can also be examined in different exclusive decay processes, e.g. $\chi_{c1} \rightarrow VV$ and $\chi_{c2} \rightarrow VP$. A detailed study of these two decays can be found in Ref. [32]. We summarize the results as follows:

i) Since $\chi_{c0,1,2}$ are P -wave states, the short-distance transition probes the first derivative of the $c\bar{c}$ wavefunction at the origin, which however, would be suppressed in $\chi_{c1} \rightarrow VV$ and $\chi_{c2} \rightarrow VP$ due to the HSR.

ii) Experimentally, the branching ratio of $\chi_{c1} \rightarrow K^{*0}\bar{K}^{*0}$ is at order of 10^{-3} [20], which appears to be sizeable, and implies a violation of the HSR.

iii) The introduction of the intermediate meson loops provides a dynamic mechanism in this process. By annihilating the $c\bar{c}$ at long distance via the intermediate meson loops, the helicity selection rule can be evaded.

iv) For $\chi_{c1} \rightarrow VV$, since the intermediate D_s and D_s^* pair has higher mass threshold, the production of the $\phi\phi$ will be relatively suppressed in comparison with the non-strange $\rho\rho$ and $\omega\omega$ apart from the final-state phase space differences. This corresponds to the flavor symmetry breaking at leading order.

v) For $\chi_{c2} \rightarrow VP$, significant U -spin symmetry breaking implies a larger branching ratio for $\chi_{c2} \rightarrow K^*\bar{K} + c.c.$ than for $\chi_{c2} \rightarrow \rho\pi$. This prediction can be examined by BESIII experiment.

In brief, we find that the intermediate hadron loop transitions provide a natural mechanism for the evasion of the helicity selection rule as a long-distance transition. It could also be a mechanism for several existing puzzles in the charmonium energy region. Systematic studies of various processes may allow us to put together pieces of information and gain much deeper insights into the underlying dynamics.

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